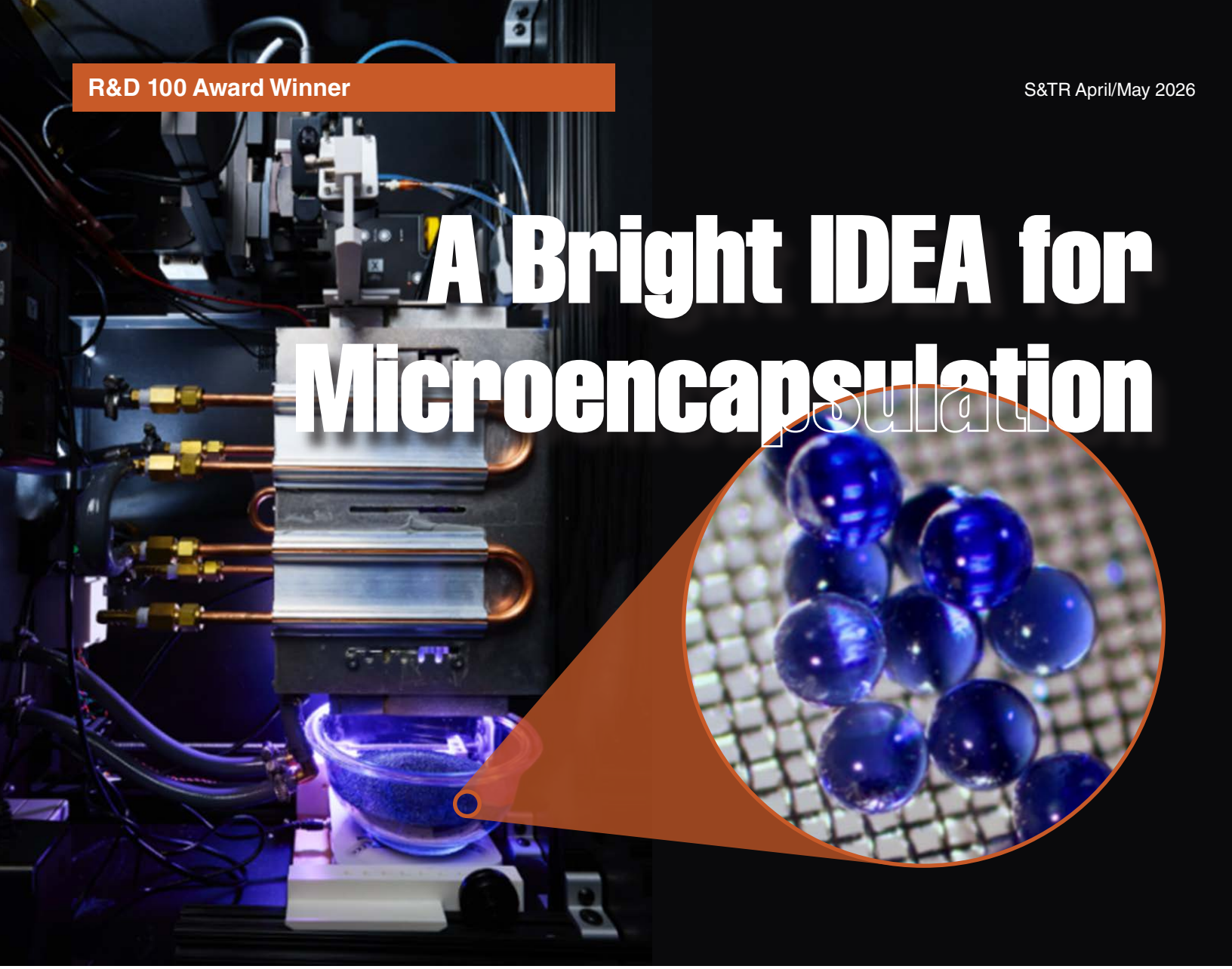
A Bright IDEA for Microencapsulation



The latest in-air drop encapsulation apparatus (IDEA) iteration uses a single nozzle and can produce approximately 130 grams of microcapsules per hour. The inset image shows a close-up of the microcapsules.

Livermore researchers are constantly tackling new problems in science and technology and striving to address unmet needs. The Laboratory's 2025 R&D 100 Award–winning technology creating a new method for microencapsulated material fabrication at high quantities is no exception. Initially driven by a need for microencapsulated carbon dioxide sorbents (MECS), Congwang Ye, a staff engineer in the Materials Engineering Division (MED), went to work creating the in-air drop encapsulation apparatus (IDEA) technology.

MECS, small beads that absorb carbon dioxide (CO_2), can work as sieves to capture carbon from the surrounding environment in both large-scale carbon sources, such as power plants, and integrated carbon removal systems. Their proper function requires a thin, CO_2-permeable shell surrounding a solvent-based interior core. Beyond carbon absorption, similar capsules could benefit many fields, such as pharmaceuticals, cosmetics, textiles, or any other industry requiring a material to be released at a certain time, responsive to stimulus, or protected from external effects.

Unfortunately, traditional manufacturing techniques are slow for such specialty microcapsules, meaning that the high demand—for as much as kilogram-quantities of MECS—has historically been impossible to make at reasonable timescales. A microfluidics technique can be applied to meet the challenge by operating multiple units in parallel, but it requires a continuous fluid medium and produces wet microcapsules that need to be washed and dried after production, adding up to multiple days to

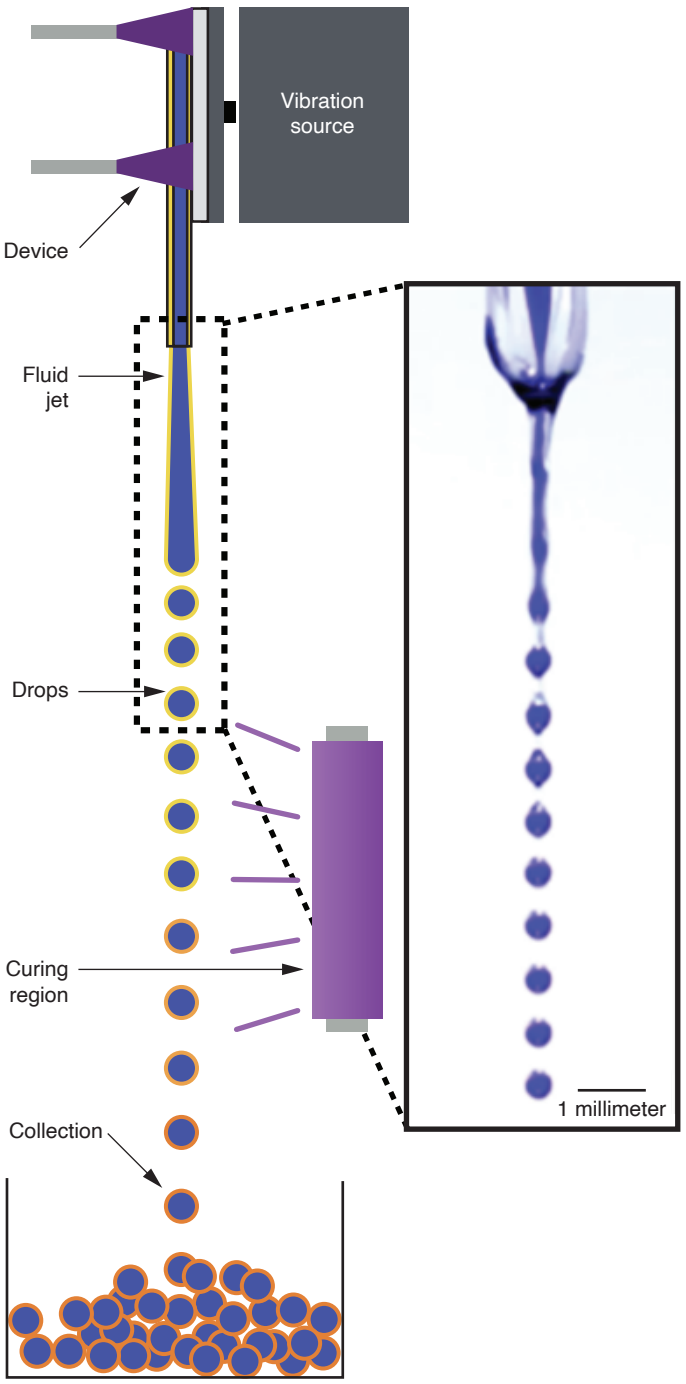
the manufacturing time. “We talked to excited potential users of the MECS material and ran into a consistent challenge; many said that they were ready to buy a kilogram of the product tomorrow,” says Ye. “Such a timeframe was not possible at all because, using the microfluidic system, we could only make microcapsules in gram-per-hour throughputs.”

An IDEA Is Born

Inspired by this unmet need, Ye evaluated several other existing options for microcapsule production including coating, freeze-drying, emulsification, extrusion, and spray drying. None could produce the encapsulated material in the quantity, quality, and cost required for commercialization, so he turned to a different option: in-air curing. This process does not involve capsules in solution; rather, droplets are formed and solidified almost instantly in air using ultraviolet (UV) light. “In this case, the droplets are created in midair and fully cross-linked into microcapsules before they hit the collection at the bottom,” says Ye. “This process significantly shortens the cross-linking and encapsulation time. The technique could also lead to a much faster turnaround in addition to the already improved production rate, which is about two orders of magnitude higher than traditional microfluidics.”

For successful in-air curing, the liquid dropped from the device would have less than a second to solidify in midair. Ye experimented with several variables in the setup, including the UV irradiation region, temperature control, and chemical composition of the liquid for curing. Despite initial difficulties, he achieved a breakthrough when drops formed blobs with a partially solid external shell—an indication that the idea was viable. Further atmosphere control and adjustments to the droplet generator to incorporate air shearing and a high-flow nozzle enabled microcapsules to not only form properly, but also to reach the ideal size of about 0.5 millimeters for optimal surface area and handleability. IDEA team member and MED research engineer Michael Triplett contributed to improved enclosure design for the IDEA technology and continues to explore ways to push the apparatus to higher throughput capabilities. “Now that we know the concept works, we can address questions such as how to capture the capsules once they’ve been produced, move them out into storage, quality control them, and improve the reliability of the tool,” he says.

The current IDEA iteration can produce approximately 130 grams of microcapsules per hour through its single nozzle while ensuring the microcapsules are highly uniform and do not require drying before being stored. The core-to-shell ratio is about 3.3:1, which means that each bead contains a relatively large amount of reactive inner sorbent, also a noticeable improvement over traditional microfluidics techniques. IDEA is also extremely rapid compared



IDEA produces dry and ready-to-use microcapsules in less than a second. After droplets are created, they pass through an ultraviolet curing region where their exteriors harden.

Development team for IDEA: (top row from left) Michael Triplett, Marcus Worsley, Kevin Paulsen, Julie Mancini, Andrew Pascall, Will Smith, and Kenneth Enstrom; (bottom row from left) Brandon Wells, Congwang Ye, and Elaine Lee. Not pictured: Jesse Ahlquist, Caitlyn Krikorian, James Oakdale, Roger Aines, Sarah Baker, Eric Duoss, and Joshua Kuntz.

to prior methods, representing a truly cutting-edge breakthrough for microcapsule fabrication. Ye says, "In the IDEA system, the length of time from the moment the droplets leave the nozzle to the moment that a user can collect the dry capsule ready for use is less than a second."

Recipe for Success

Lawrence Livermore's dedication to mentorship, specifically in the realm of entrepreneurship and collaborations, offered a boost to IDEA's commercial success. Ye had minimal experience in technology commercialization prior to developing IDEA. He credits the Laboratory's Innovation and Partnerships Office (IPO); commercialization training programs, such as Energy i-Corps and National Labs Entrepreneurship Academy; and scale-up and technology development guidance tools, such as the Livermore Risk Assessment and Mitigation Protocol (L-RAMP), which came out of a Laboratory Directed Research and Development (LDRD) Strategic Initiative (SI) project. The training and support grew his understanding of market needs so he could demonstrate the innovation offered by IDEA in the best way possible. The LDRD SI aims to develop Livermore science and technology and institutional capabilities for bringing more technologies to the scale needed for industry. "Many Laboratory technologies perform well at bench scale and generate a great deal of industry interest but can face challenges connecting with industry collaborators," says Ye. "I want to leverage my experience from developing and commercializing IDEA to help build those connections."

While developed with carbon capture in mind, IDEA is a versatile encapsulation platform suitable for different applications, especially biological ones. Microcapsules are well-suited to store living cells for the purposes of tissue development or bioreactor systems. Unlike a standard gel that houses loose cells, the structure of microcapsules enables nutrients to disperse and reach cells evenly without diffusion issues. This property creates a larger bulk volume of stored cells—a volume possible to produce because of IDEA's high throughput. IDEA's use to biological applications was tested and verified during an LDRD project in which the team successfully produced microcapsules with living cells in the center that remained viable after the encapsulation and storage processes. IDEA is especially advantageous for such applications because, unlike traditional techniques, it does not require the use of continuous fluid such as oil or reactive liquid, which adds complication to the process and reduces cell viability.

Bolstered by the recognition of an R&D 100 Award, the team is working to increase IDEA's throughput further with a multinozzle fabrication head, as well as making progress with a start-up company to begin material production at their facility for real-world use. "The technology offers promise in carbon capture and other applications where the rapid production of these microcapsule materials could be hugely beneficial, so I'm glad to see that that promise was recognized with this award," says Triplett. Adds Ye, "I want to thank Livermore's IPO and the R&D 100 Award competition for their interest in seeing a technology not just being invented but also making a real-world impact."

—Lilly Ackerman

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